# EVOLUTION OF S1'-100 SYSTEM DESIGNS

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## Abstract

The current phase of the SP-100 program was initiated in 1986 with the objectives of developing the technology for Space Reactor Power Systems (S RPSs) in the 10 1000 kWc power range and performing ground system tests of both nuclear and non-nuclear major assemblies. During the course of this development, several system designs at different power levels have evolved, The design activities cover power levels from 5-- 100kWc, technology ranging from currently available through projected evolution, and incorporation of features to enhance survivability. The designs demonstrate the adaptability of the basic technology developed in the SP-100 Program. A summary is provided of the key features and attributes of each of the design adaptations of SP-100 technology and the mass-power relationship that the designs imply. Conclusions regarding the applicability of the SP-100 system to near-tmn and future mission applications arc provided in the context of currently available technology and the improvements that could result from continuation of technology development activities.

## IN' 'RODUCTION

This paper describes SP-100 system designs that have evolved in response to both programmatic and user needs during the course co the program. These designs have formed the basis for detailed design of components, subsystems and assemblies, as wc]] as providing the requirements for the planned system-level tests. Additionally, especially in the latter years of the program, system designs were conceived in conjunction with specific early mission-related planning activities, and thus provided the information needed by potential users as they studied applications requiring space nuclear power.

The paper provides a historical background of the designs that have evolved and then describes the most important systems in terms of requirements and key design features. Other designs performed at a more conceptual level are noted inthcfollowing.section. A summary of performance characteristics is included that shows the relationsh ips of power, mass, and technology maturity.

## HISTORICAL KVOL(J'1'1ON

The evolutionofSP-100systcn] designs was governed primarily by user requirements. At the beginning of the current phase of the program in FY 1986, the. threat posed by the Soviet Union of attacks using intercontinental ballistic missiles was being addressed by the Strategic Defense Initiative Office (SDIO). The SDIO was pursuing space-based defensive systems that could use SRPS designs with power ratings of -100 kWc or greater (a 300 kWc design was initially considered but not fully developed) for more advanced concepts. Future NASA missions to the outer planets using electric propulsion could also use SRPS designs with power ratings approaching 100 kWc.

Thus, the scalable technologies being developed in the SP-100 Program were used as the basis for a 100- kWc Generic Flight System (GFS) design. Although the basic GFS was not hardened to withstand hostile threats, a key consideration in evolving the design was case of hardenability to meet SDIO requirements. This allowed the effort to focus initially on developing technologies needed to meet basic performance requirements. The parallel development of hardening technologies for the military sector was followed so that they could effectively be integrated into a hardened design. The GFS design effort initiated in FY 1986 was maintained throughout the SP-100 Program. It was used to prioritize technological development activities from the perspective of importance to the overall system design.

Because studies had indicated that Sprm-based nuclear reactors were inherently more capable of withstanding hostile threats than solar arrays, 10-40 kWe hardened designs suitable for Air Force missions were formulated in FY 1989. The design incorporated features to meet classified requirements provided by the Air Force. A 30 kWe conceptual design for another classified application was also completed in this time period.

During the FY 1990-1991 time frame, the Soviet Union ceased to be a unified force and the threat of attack correspondingly diminished. This resulted in a decreased emphasis on early deployment of SDIO and Air Force space-based defensive systems. However, requirements for NASA missions remained. Mission studies (Kelly rind Yen 1992) showed that combining an S1'- 100 SRI'S with electric propulsion would permit spacecraft to rendezvous with outer planets. their moons, and asteroids. This rendezvous capability provided by an SP-100 Nuclear Electric Propulsion (NEP) system greatly increases the science return as compared to ballistic flyby missions. Furthermore, the mission duration was reduced significantly and the practicality of missions to the outer planets was thereby markedly improved.

Following the diminution of the Soviet threat, funding priorities were shifted and planning of NASA missions was constrained to pursue lower-cost missions involving lower powers, smaller spacecraft, and less expensive launch vehicles. Studies in FY 1992 delineated seven optional system designs in the 5-15 kWe power range where already - developed S1'- 100 technology could be implemented and could be employed in an early mission. Onc example looked at in some detail was an extensive three-year investigation of plasma physics phenomena in the Van Allen belts by an NEP-powered spacecraft spiraling through the radiation fields.

in FY 1993, 20 kWc SRPS designs, based on using already-dcvclopcd technology, were created for planetary and asteroid missions. The 20-kWe SRPS designs, when used to power electric propulsion thrusters, could perform science missions of approximately five-year duration, including a rendezvous with main belt asteroids or the moons of Mars.

Under IR&D funding, Martin Marietta, the S1'- 100 System contractor, also performed several design studies for lunar surface power and orbital applications (Armijo et al. 1991).

## SYSTE 1 REQUIREMENTS AND DESIGN DESCRIPTIONS

Kcy system requirements and design features of selected designs discussed in the previous section arc presented below.

### Generic Flight System

The 100 kWc GFS design was conducted in the initial part of the development phase to support the Nuclear Assembly Test (NAT) ant], subsequently, the planned Integrated Assembly Test (IAT). This fully documented design formed the basis for all of the component development work accomplished to date. A major design update was accomplished in 1992 to reduce the mass of the total system.

Key requirements for the updated GFS design arc presented in Table 1. The full set of requirements (Shepard and Stephen 1992) expands on these requirements and specifically encompasses (1) safety, (2) thaw and start-up, (3) environments including launch, ascent, operating orbits and meteoroids and space debris, (4) materials and associated processes, (5) assembly, and (6) testability. The performance and design characteristics of the updated GFS that resulted from imposing these requirements arc presented in T'able 2. Note that the reactor outlet temperature rises from 1350 K at the Beginning of Mission (BOM) to 1375 K at the End of Mission (EOM). This rise is necessary to maintain a constant power- output of ] 00 kWe while compensating for degradation of thermoelectric materials and the loss of radiator effectiveness due to damage from meteorods and space debris. Design features are summarized in "1'able 3.

The physical configuration of the updated design (GE Astro Space Division, 1993) is depicted in Figure 1. The reactor and shield arc located at the apex of the conical Reactor}'owcr Assembly (RPA). The piping of the primary heat transport loop serves as assembly joints between the RPA and Energy Conversion Assembly (ECA). The 12-panel deployable radiator is connected to the ECA, where assembly joints include connection with secondary loop heat rejection ducts. The enlarged Pump/PCA segment shows alternating thermoelectric electromagnetic (TEM) pumps and power conversion assemblies (PCAs). Adjacent Pump/PCA units arc linked to prevent backflows that inhibit performance, particularly during startup involving progressive thaw of the frozen lithium working fluid usc(I in both the primary and secondary heat transport loops.

TABLE 1. Key Generic Flight System Requirements.

| | |
|---|---|
| Opel-ational Life | 10 years total with a maximum of 7 years at full power |
| Launch Vehicle | Titan IV/Centaur |
| Mission Operation Orbit | 2(NO km altitude circular earth mbit at 28° inclination |
| User Interface Plane | 4.5-m diameter separated by 22.5 m from the base of the reactor vessel |
| Self-~cncratcd Radiation at User Inter-face Plane | Neutron Fluence: $1 \times 10^{13}$ n/cm$^2$ (1 McV equivalent)<br>Gamma Dose: $5 \times 10^5$ rads (Si)<br>Thermal Power Density: 0.14 W/cm$^2$ |
| Main Bus Electrical Power To User | 99.7 kW at 200 Vdc ± 7 Vdc<br>300 W at 28 Vdc ± 7 Vdc |
| Maximum Systems Mass | 4600 kg |

TABLE 2. Generic Flight System Performance/Design Characteristics.

| | |
|---|---|
| Key System Performance Characteristics | |
| Rated Electrical Power Output (kWe) | 100 |
| BOM Reactor Outlet Temperature(K) | 1350 |
| EOM Reactor Outlet Temperature (K) | 1375 |
| Reactor Thermal Power Required (kWt) | 2400 |
| Average EOM Radiator Temperature (K) | 791 |
| Key System Design Characteristics | |
| Launch Vehicle | Titan IV/Centaur |
| Shield Half-cone Angle (deg) | 17 |
| Separation Distance (m) | 22.s |
| Deployable Boom | Yes |
| The.rmopilc Area (m$^2$) | 7.08 |
| Radiator 1 -Side Physical Area (m$^2$) | 106 |
| Power Distribution Voltage (Vdc) | 200 |
| Number of Thermoelectric Elements | |
| Power Conversion | 8640 Cells |
| Auxiliary Cooling and Thaw (ACT) | 180 Cells |
| Thaw I'revisions | NaK Tracelines |
| Mass by Subsystem (kg) | |
| Reactor | 700 |
| Shield | 960 |
| Heat Transport (Includes thaw battery, if required) | 520 |
| Reactor Instrumentation and Control (I&C) | 320 |
| Power Conversion | 450 |
| Heat Rejection | 1040 |
| Power Conditioning, Control and Distribution (PCC&D) | 390 |
| Mechanical/Structural | 220 |
| Total | 4600 |
| System Power-to-Mass Ratio (W/kg) | 21.7 |

TABLE 3. Generic Flight System Design Features.

| | |
|---|---|
| Reactor Design Features | |
| Auxiliary Cooling Loop | Yes |
| Reentry Shield | Yes |
| Reactor Structural Material | PWC-11 |
| Fuel | UN |
| Safety Rods | In-core |
| Control Elements | Peripheral Sliding |
| Shield Subsystem Design Features | |
| Neutron Shield Material | $LiH/B_4C$ |
| Gamma Shield Material | U238 |
| Primary Heat Transport Subsystem Design Features | |
| Number of Primary Loops | 6 |
| Pump Type | TEM |
| TEM Pump Thermoelectric Material | SiGe/GaP |
| Reactor I&C Subsystem Design Features | |
| Signal/Control Multiplexers | Yes |
| Power Conversion Subsystem Design Features | |
| Thermoelectric Material | SiGe/GaP (BOM Z = 0.86 E-3/K) |
| Thermoelectric Cell Type | Conductively Coupled |
| Heat Rejection Subsystem Design Features | |
| Number of Secondary Loops | 12 |
| Radiator Type | 12 Deployable Panels C-C/Ti Heat Pipes |
| Secondary Piping/Radiator Duct Material | Titanium |

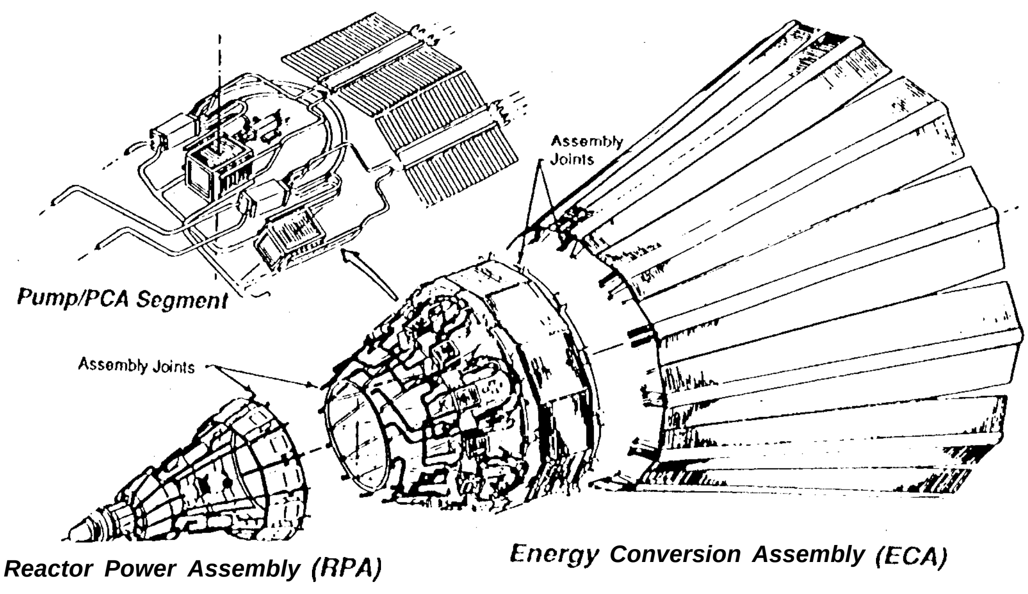


FIGURE 1. Updated Generic Flight System Physical Configuration.

As noted in I'able 1, the GFS is required to operate in a high 2000-km orbit. When contemplating missions m the outer planets, the GFS design can be simplified to reduce mass. The conical carbon-carbon reentry shield enclosing the reactor can be jettisoned following insertion into a trajectory that ensures escape from the Earth's gravitational field. The auxiliary cooling 100p (ACL) that prevents overheating and associated possible dispersal of reactor core materials in the event of a loss-of-coolant accident is not needed for a reactor in outer space. Because of greatly reduced safety requirements, the number of in-cm safely rods can be reduced from 3 to 1, Removal of the ACL and reduction in the number of safety rods reduces the reactor diameter and size of the shield. With these changes as the leading factors among a set of changes, it was estimated that the mass of a GFS tailored for missions to the outer planets would be ~3930 kg.

## 10-40 kWe Hardened Designs

in FY 1989, hardened 10–40 kWc designs (Shepard 1989 and Schmidt 1989) were generated to serve as power sources for potential U.S. Air Force missions that required systems capable of surviving hostile threats. The requirements for the study were based on military reactor performance goals including the capability to meet increased "G" levels in any direction for the deployed configuration. The selected design included a compact core with peripheral control and safety rods, wireless fuel pins, double-wall construction for the primary loop, elimination of the secondary loop, and hardened radiator and multiplexer designs.

Key requirements for the 1&40 kWc hardened designs are given in "1'able 4. The designs are to employ the SP- 100 GFS technology for the reactor and thermoelectric converters. The central focus was to harden the SRI'S to withstand hostile threats. Specific threats anti hardness levels associated with "SUPER" and 1.3 SMATH I/JSC1 are addressed in the classified literature (Schmidt i 989). The "SUPER" hardness requirements were based on the projections in FY 1989 of Soviet weapon systems under development at that time, whereas 1.3 SMATH I/JSC1 was reflective of the capabilities of existing or more near-term weapon systems.

A key result from the study is presented 'in Figure 2. To provide features to withstand the "SUPER" hardness level results in a significant mass penalty relative to the 1.3 SMATH I/JSC 1 level, eg., - 500 kg for a 10- kWe SRPS. Of the

TABLE 4. Requirements For Hardened 10- 40 kWc Designs.

| |
|---|
| • Reactor and Power Conversion Technology Limited to that being developed under the SP- 100 Program |
| • 10 Year On-orbit Design Life at Rated Output Power |
| • Self-irxiuccd Radiation Environment at User Plane<br>- Gamma Rays 0.5 MRAD (Si)<br>- Neutrons 1 x 10]$^3$ n/cm$^2$ (1 McV Equivalent) |
| • 4-m Diameter User Interface Plane |
| • S1'-100 GFS Safety Requirements |
| • Fixed Structures Sized for Titan IV Launch Loads |
| • Hardened to Both "SUPER" and 1.3 SMATH I/JSC1 Laser and Nuclear Threats |
| • Deployable Structures Sized For 0.3 G Lateral Loading |
| • Electrical Power Supplied on Two Busses<br>-300 Watts on Secondary Bus at 28 +/-7 Vdc<br>- Balance of Rated Power on Main Bus<br>100 Vdc +/-5% For Output Power Rating < 20 kWc<br>200 Vdc +/-5% For Output Power Rating ≥ 20 kWc |

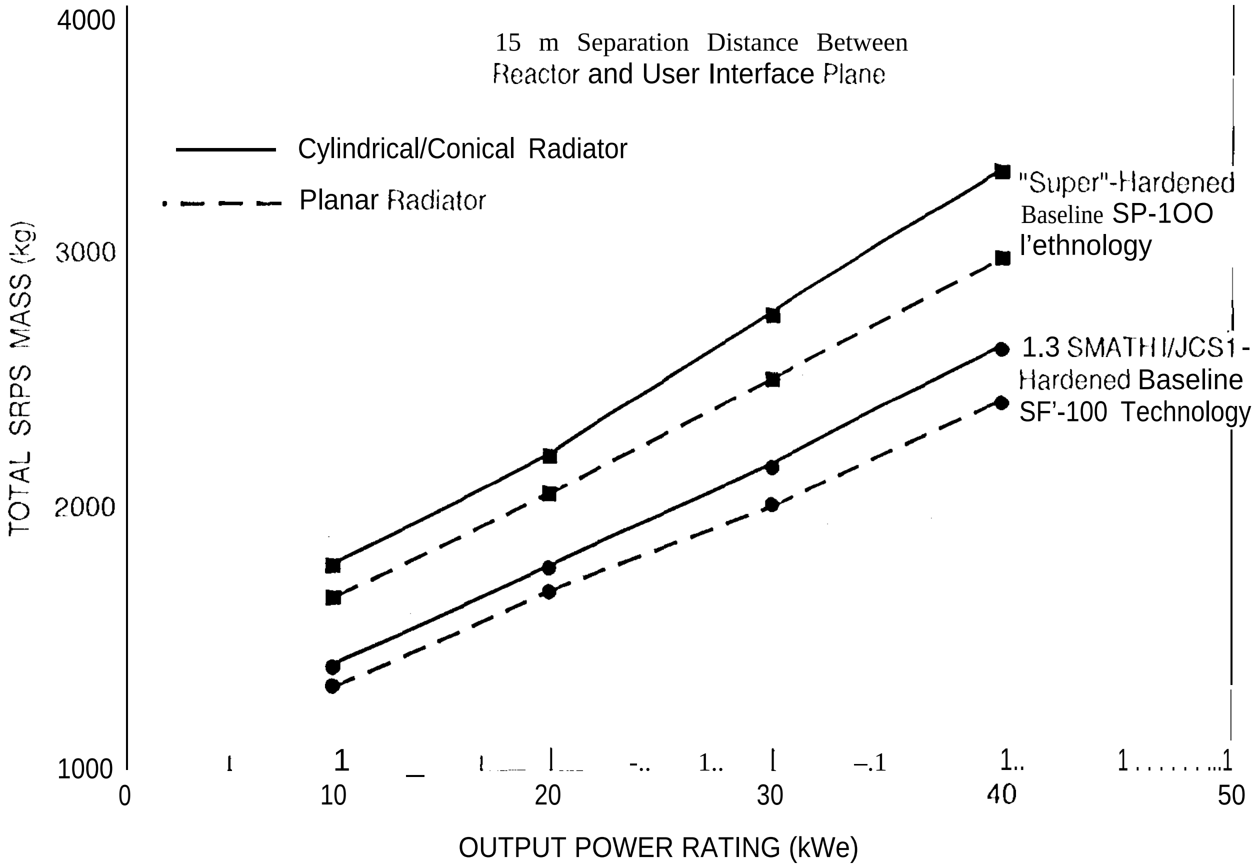


FIGURE 2. Effect of Hardness Level and Radiator Configuration on Mass of Hardened Designs.

two hardened radiator configurations studied, the smaller planar radiator more effectively dissipates external thermal loads (lasers) and thereby provides a mass savings, where the mass savings arc greater at higher power levels.

## 5-15 kWe Early Technology Designs

in FY 1992, an option was pursued for a significantly less expensive first flight of the SP- 100 system that could bc launched in this decade (GE Astro Space Division, 1993). The approach was based on employing an earlier stage of technology for systems in the 5 – 15 kWe power range, and saving both time and cost by using the qualification system as the flight al-title. Requirements arc given in-Table 5. In addition to use of SP-100 thermoelectric converter technology, the ground rules for this effort allowed consideration of converters developed for Radioisotope Thermoelectric Generators (RTGs).

This effort resulted in the following seven conceptual design options and launch elate opportunities based on start of implementation in FY1993:

- Option A • Maximum usc of prototypic GFS components fora 15- kWc system capable of an FY 1999 launch elate
- Option B • Same as Option A except that reactor Size is optimized for the required thermal output
- Option C • Same as Option B except that established, but non-prototypic, electrical trace heating is used for thaw and the deployable boom is eliminated to permit an FY 1997 launch date
- Option D • Lower power version (7.5 kWc) of Option C to permit integration with a Delta II launch vehicle

TABLE 5. Requirements For Early Technology Designs.

| | |
|---|---|
| • Rated power: | 5 [0 15 kWe (varied to accommodate launch vehicle constraints) |
| • operational lifetime: | 1.5 years at rated power<br>2.0 years total on-orbit lifetime |
| • User plane diameter: | 3.6 meters (for Atlas I] AS)<br>2.6 meters (for Delta 11) |
| • Self-generated radiation environments at user interface plane: | Neutron fluence = 1.S1{13 n/cm$^2$<br>Gamma Dose = 1 .5E5 rads (Si) |
| • Distribution voltage: | 1 00 Vdc or less |
| • Launch vehicle: | Atlas IIAS and Delta II |
| • GFS Safety requirements | |

TABLE 6. 5-15 kWe Orbital Flight Options Performance/Design Character-istics.

| | OPTIONS | | | | | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G |
| Key System Performance Characteristics | | | | | | | |
| Rated Electrical Power Output (kWe) | 15 | 15 | 15 | 7.5 | 10 | 10 | 6 |
| EOM Reactor Outlet Temperature (K) | ]375 | 1375 | 1375 | 1375 | 1375 | 1375 | 1375 |
| Reactor Thermal Prover Required (kWe) | 450 | 450 | 450 | 225 | 275 | 275 | 175 |
| Average EOM Radiator Temperature (K) | 760 | 760 | 760 | 760 | 520 | 520 | 585 |
| Key System Design Characteristics | | | | | | | |
| Launch Vehicle | | | | | | | |
| - Atlas IIAS | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| - DELTA 11 | | | | ✓ | | | ✓ |
| Shield Half-time Angle (deg) | r7 | 17 | 17 | 17 | 14 | 14 | 12.5 |
| Separation Distance | 15 | 15 | 6,5 | 10 | 6.5 | 6.5 | 3.7 |
| Deployable Boom | Yes | Yes | No | Yes | No | No | No |
| Thermopile Area (m$^2$) | 1.14 | 1.14 | 1.14 | (),57 | 0.32 | 0.206 | 0.125 |
| Radiator I-Side Physical Area (m$^2$) | 21 | 21 | 21 | II | 35 | 35 | 12 |
| Power Distribution Voltage (Vdc) | 100 | 100 | 100 | too | 50 | 50 | 50 |
| Number of Thermoelectric Elements | | | | | | | |
| - Cells | 1680 | 1680 | 1680 | 840 | | | – |
| - Multicouples | | | | | 5000 | - | |
| - Unicouples | | | | | | 12,000 | 719? |
| Thaw Provisions | | | | | | | |
| - NaK Tracelines | ✓ | ✓ | . | | | | |
| - Electric Heaters | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Mass by Subsystem (kg) | | | | | | | |
| Reactor | 800 | 600 | 500 | 395 | 395 | .395 | 395 |
| Shield | 730 | 7.30 | 770 | 710 | 720 | 720 | 6?5 |
| Heat Transport (Includes thaw battery, if required) | 140 | 140 | 320 | 150 | 235 | 235 | 133 |
| Reactor I&C | 340 | 330 | 220 | 220 | 220 | 2?0 | 220 |
| Power Conversion | 85 | 85 | 85 | 55 | 155 | 210 | 184 |
| Heat Rejection | 215 | 215 | 215 | 130 | 95 | 95 | 60 |
| PCC&D | 16S | 165 | 150 | 130 | 130 | 130 | 90 |
| Mechanical/Structural | 140 | 138 | 119 | 104 | 102 | 105 | 90 |
| Total | 2615 | 2403 | 2379 | 1894 | 2052 | 2110 | 1797 |
| System Power-to-Mass Ratio (W/kg) | 5.7 | 6.3 | 6.3 | 4.0 | 4.9 | 4,7 | 3.3 |

Option E •Uses existing converter technology (for example, radiatively coupled Mod RTG multicouples) for a 10 kWe system to accommodate an FY 1996 launch date

Option F •Uses existing radiatively coupled RTG unicouples for a 10 kWe system to accommodate an FY 1996 launch date

Option G •Lower power version (6 kWe) of Option F to permit integration with a Delta II launch vehicle

The performance and design characteristics of the above options are presented in Table 6.

For Option A, packaged for launch in an Atlas II AS, an identified mission involved the powering of an ion electric propulsion system to boost a plasma physics science platform from low earth orbit to the L1 Lagrange point over an approximate two-year period of thrusting in a spiral trajectory.

## 20-kWe SRPS Using Closed Brayton Cycle

In late FY 1992, a joint NASA/DOE Team on Space Nuclear Power and Propulsion conducted an assessment of the SP-100 Program and recommended that it should proceed to develop a flight system using the liquid metal cooled fast spectrum reactor technology of the current program in conjunction with a Closed Brayton Cycle (CBC) power conversion subsystem. This latter technology was selected because it had been developed and could support an early flight in this decade should NASA decide to proceed with a nuclear electric propulsion (NEP) interplanetary mission. In response to this recommendation, DOE redirected the program and a system design activity was initiated.

Table 7 summarizes the key requirements for the CBC-based design. These requirements were predicated on a three-body spacecraft concept intended to perform an NEP mission to the inner planetary region. Shepard (1992) provides a complete set of requirements for this system.

Table 8 provides a summary of several of the principle design parameters of the CBC SRPS design, The design consists of three basic parts: (1) the Power Generating Module (PGM), (2) the Electric Propulsion Module (EPM), and (3) the Payload Module (PLM). A deployable boom connects the PGM to the EPM, while a second boom links the PLM to the EPM, which is located at the center of mass. The design employs a small reactor producing 110 kWth of thermal power but retains the GFS fuel pin size. Two CBC units are used, one of which is for redundancy. A fixed conical radiator based on Space Station Freedom design concepts rejects the waste heat to space. A deployable planar radiator option, while more complex, would result in a lower mass. A TEM pump is used to transport the lithium coolant from the reactor to a heat exchanger and He-Xe gas provides heat to the CBC unit. Toluene or a similar organic fluid is employed in the tertiary heat rejection loop. Table 8 contains pertinent CBC performance data, and Table 9, key reactor design parameters. Shepard (199~a, 1993b) provides additional design details.

TABLE 7. Primary Requirements for 20-kWe CBC System.

| | |
|---|---|
| Operational life | 5 years total with a maximum of 3.5 years at full power |
| Launch vehicle | Titan 4/Centaur |
| Dose plane definition | 2.5-m diameter separated by 8 m from the base of the reactor vessel |
| Self-generated radiation at dose plane | Neutron fluence: $1 \times 10^{13}$ n/cm (1-MeV equiv)<br>Gamma dose: $5 \times 10^{5}$ rads (Si)<br>Thermal power density: 0.14 W/cm$^2$ |
| Main bus electrical power to user | 20 kW |
| Main bus voltage and frequency | 208 Vac ±5% (line-to-line), 3 phase, 600 Hz |
| Secondary bus electrical power to user | 300 W |
| Secondary bus voltage | 28 Vdc ±5% |
| Maximum system mass | 2800 kg |

TABLE 8. CBC System Performance Parameters.

| PARAMETER | VALUE: Fixed Conical/ Cylindrical Radical | VALUE: Deployable Planar Radiator |
|---|---|---|
| Net Electrical Power Output (kW) | ?0 | 20 |
| Reactor Thermal Power (kW) | 110 | 110 |
| Main Radiator Area ($m^2$) | 59 | 43 |
| TEM Pump Radiator Area ($m^2$) | 0.35 | 0.35 |
| SRI'S Mass (kg)* | | |
| Reactor | 480 | 480 |
| Shield | 460 | 460 |
| Primary Heat Transport | 130 | 130 |
| Reactor I.&C | 170 | 170 |
| Brayton Power Conversion** | ***770*** | ***770*** |
| Heat Rejection | 390 | 310 |
| PCC&D | 175 | 175 |
| Mechanical/Stnrctural | 260 | 260 |
| Total | 2835 | 2755 |

Includes PGM-to-EPM deployable boom, primary and secondary batteries for 100% margin during start-up and 25% margin for shutdown/restart (assumed duration of 4 hours), and transformer/ rectifier to supply 28 Vdc secondary and recharge batteries

* includes two redundant CBC units

TABLE 9. CBC System, Key Reactor Design Parameters

| PARAMETER | VALUE |
|---|---|
| Thermal Power (kW) | 110 |
| Number of Fuel Pins | 947 |
| Fuel Pellet Diameter (mm) | 6.4 |
| Liner | Free Standing Re |
| Fuel Column Height (cm) | 23 |
| Reactor Diameter (cm) | 30 |
| Number of in-core Rods | 2 (Dual Function) |
| Auxiliary Cooling Loop U-tubes | None |
| Fuel J'in Peak Linear Power (kW/m) | 1.0 |
| Fuel Pin peak Burnup (a/o) | 0.42 |

A design review concluded that the development of a flight system employing the CBC SRPS approach was feasible for an early mission. No major CBC development issues were identified, although normal engineering development for this specific application would be required. The reactor and balance of system posed no significant problems for an early flight.

## 20- kWe Thermoelectric Design

in early FY 1993, it became clear that an early C}lC-based S1'- 100 mission was unlikely and a decision was rnadc to generate a 20 kWe thermoelectric (TE) design, the primary rationale being that given additional development time, the thermoelectric converter based design would be more competitive in terms of mass and lifetime capability.

As with the CBC design, requirements were based on an NEP interplanetary mission. "1'able i 0 summarizes the top-level design ground rules. Shepard ( 1993c) developed detailed requirements for this design. Table i i summ - rizes key design and performance features of the 20 kWe TE system.

TABLE 10. Primary 20 kWe Thermoelectric SRPS Design Ground Rules.

- Launch on Titan IV / Centaur.
- 5-year mission duration, including 3.5 years at rated power.
- 20 kWe supplied to thrusters.
- Use nuclear assembly test fuel pellets.
- It is permissible for the thermoelectro-magnetic pump and gas separator/accLrmulator designs to be scaled from the test unit implementations to reduce tile mass of the 20- k We system provided that this scaling will not require additional technology development.
- Use a three-bociy spacecraft as the basis for the 20- kWc flight system design (establishes a 2.5-m dia. dose plane located 8 m from the reactor/shield interface plane).
- '1'here is no requirement for a scram function.
- Restart after shutdown is to be accommodated provided that duration of battery discharge does not exceed 1.S hours.
- Mass goal is 2S00 kg or less.

TABLE 11. 20-kWe Thermoelectric Design, Key System Design and Performance Parameters.

| PARAMETER | VALUE |
|---|---|
| Electrical power delivered to user at EOM (kW) | 20.6 |
| Electrical power generated by power converters at EOM (kW) | 22.4 |
| Reactor thermal power required at EOM (kW) | 596 |
| EOM reactor outlet temperature (K) | 1375 |
| EOM reactor inlet temperature (K) | J 293 |
| Total flow through reactor at EOM (kg/s) | 1.608 |
| Secondary flow per radiator panel (kg/s) | 0.258 |
| Radiator inlet temperature at EOM (K) | 825 |
| Radiator outlet temper-aturc at EOM (K) | 743 |
| Number of main Power Converter Assemblies | 6 |
| Number of TEM Pumps | 3 |
| Total thermoelectric cell area ($m^2$) | 1.56S (Main Converters)<br>0.065 (ACT Converter) |
| Auxiliary radiator one-side area ($m^2$) | 1.3 |
| Total main radiator one-side area ($m^2$) | 29.S |
| SRPS mass by subsystem (kg) | |
| Reactor | 573 |
| Shield | 710 |
| Primary Heat Transport | 1'79 |
| Reactor I&C | 185 |
| Power Conversion | 231 |
| Heat Rejection | 359 |
| Power Conditioning, Control, and Distribution | 142 |
| Mechanical/Structural | 189 |
| Total | 2568 |

The distinguishing features 01' this design arc: (1) the usc of a small reactor (approximately 600 kWth) with fixed reflectors and three dual function contred/safety rods; (?) a 4 x 6 thermoelectric cell array configuration for the converter; (3) six fixed heat pipe radiator panels; and, (4) three thermoelectro-magnetic pumps. The mass of the power system is 2568 kg, but optimization of fuel pellet diameter anti other identified refinements could bring this to approximately 2?00 kg. Chan (1993) provides additional details of this design.

## SYSTEM PERFORMANCE CHARACTERISTICS

The design implementations of SP-100 technology encompass: ( 1 ) power levels from 5 kWe to 100 kW, (?) technologies varying from a stat us of currently available to projected mature SI'-1OO Technology, and (3) applications ranging from 2-5 year Earth-orbiting missions to long-duration outer planetary missions of i 0-14 years. In Figure 3, the mass of the different designs is shown as a function of their power level. The curve for mature SP- I 00 technology shows the expected trend of increasing mass with power. Furthermore, the mass pcr unit power is lower at higher power levels. One factor contributing to this scalability characteristic favoring higher powers is that a minimum reactor size is needed to achieve criticality.

Comparison of designs using early technologies, including RTG unicouples, Si-Ge converters, and CBC with the curve for mature S1'-100 technology designs, shosw that significant mass savings (-50(-1 000 kg) will result from continuing the development of SP- 100 technology. A kcy technology effort is to develop improved Si-Ge (GaP) converters. The hardened designs arc based on mature S1'- 100 technology. The lower hardness level of 1.3 SMATH l/JSCl, corresponding to the lower bound of the shaded region, approaches the curve for mature SP-100 technology and indicates that the mass penalties for hardening to this level are relatively modest. The upper bound of the shaded region represents hardening to the "SUPER" level, where mass penalties are substantial.

At the 100-kWe power level, the GFS design when tailored for outer planet missions approaches the mature SP-100 technology curve that reflects earlier projections of the SP- 100 Project Office. The GFS design for a 2000-km orbit incorporates safety features that result in a significant increase in mass as discussed previously. The primary mission for higher powers approaching 100 kWc is now considered to be NASA outer planetary missions using electric propulsion. The orbital mission that was originally identified was targeted toward SDIO applications being considered in the decade of the 1980s.

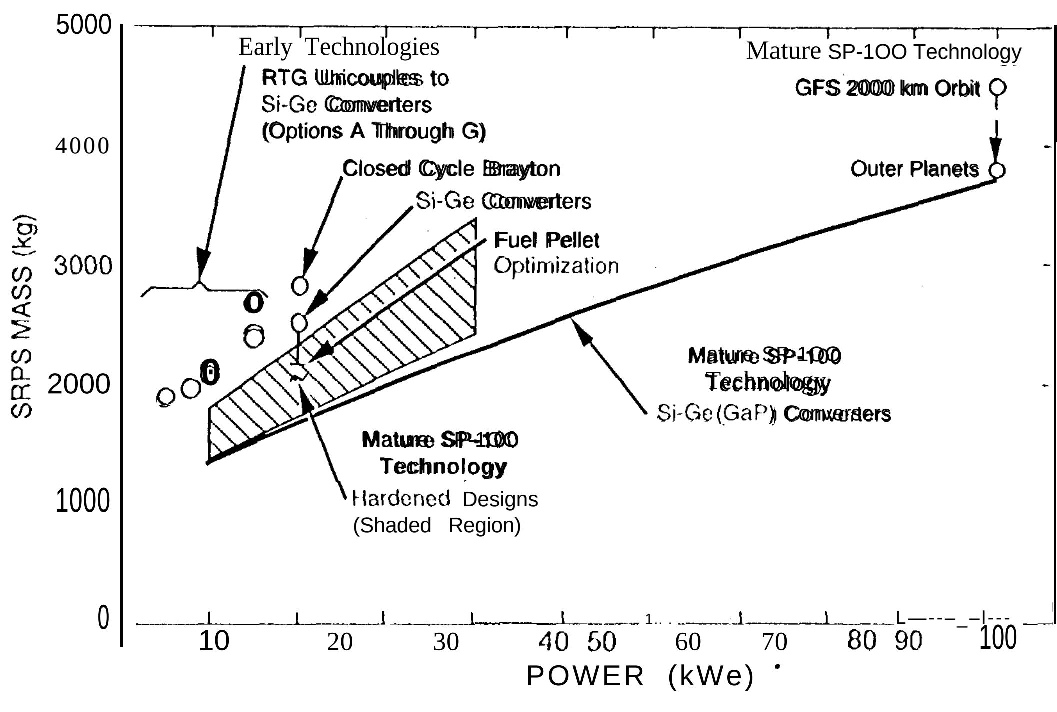


FIGURE 3. Effect of Technology Development on Mass Versus Power Relationship,

## CONCLUSIONS

By examining the evolution of S1'-100 system designs and their implications regarding the mass of the SRPS as a function of power and technology development level, the following conclusions arc drawn:

1. The existing SP-100 early technologies can bc used in the 5-20 kWe range with respective SRI'S masses of -1700 2600 kg for orbital and planetary science missions,

?. Major reductions in SRPS mass accompanied by increases in mission li fetime capability can bc achieved by continuing the effort 10 develop mature SP-100 technology and thereby enable NASA explorations of the outer planets that require 1O-14 year missions.

3. Hardening of the SRPS to 1.3 SMATH I/JSC 1 levels for military missions can bc achieved with modest mass penalties for designs based on mature SP-100 technology.

4. SP- 100 reactor technology can bc integrated with a range of converter technologies including currently existing RTG unicouples and closed-cycle Brayton units as options for early missions

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